Statically and dynamical analysis of clay stabilized with Bagheran natural pozzolan geopolymer

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Abstract

Given the increasing demand for low-carbon soil improvement techniques and the limited number of studies investigating the use of Baqeran Natural Pozzolan (BNP) for soil stabilization, this study aimed to evaluate the mechanical, dynamic, and microstructural performance of a BNP-based geopolymeric binder in CL clay. The main novelty of this research lies in the simultaneous investigation of the effects of BNP content and two types of alkaline activators (NaOH and Na_2SiO_3) on the compressive strength, dynamic simple shear response, and microstructural mechanisms of clay under ambient curing conditions. The experimental program included unconfined compressive strength (UCS) tests at curing ages of 7, 14, and 28 days, dynamic simple shear tests conducted after one day of curing under four loading amplitudes and three surcharge levels, and scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) analyses. The results demonstrated that NaOH activation produced the greatest improvement in the compressive strength of the clay. The 28-day UCS values of mixtures containing 10%, 20%, and 30% BNP were 2,400, 2,800, and 3,500 kPa, respectively. Compared with untreated natural soil at the same curing age, these values represented increases of 220%, 273%, and 367%, respectively. The dynamic simple shear test results indicated that the presence of the geopolymer and an increase in surcharge pressure led to an increase in shear modulus and a reduction in damping ratio. Furthermore, microstructural analyses revealed that aluminosilicate dissolution and the formation of a continuous gel matrix were among the primary mechanisms responsible for strength enhancement. These findings demonstrate the considerable potential of alkali-activated BNP for clay stabilization. However, further investigations, including California Bearing Ratio (CBR) tests, dimensional

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analysis, and large-scale evaluations of soil behavior, are necessary before the findings can be generalized to practical engineering applications.

Keywords: Bagheran Natural Pozzolan (BNP); Alkaline Activation; Dynamic Simple Shear; Unconfined Compressive Strength (UCS); Microstructural Behavior.

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1. Introduction

Soil stabilization through chemical reactions between soil minerals and binding agents enhances the bearing capacity of soil while reducing its compressibility and shrink–swell potential [1], [2]. Lime, a well-established soil stabilizer, along with ordinary Portland cement (OPC), has been widely used for this purpose. However, growing evidence indicates that these conventional stabilizers are associated with significant environmental concerns [3], [4]. In response to these concerns, researchers have increasingly focused on developing sustainable and cost-effective alternatives to conventional soil stabilizers [5]. Industrial by-products, such as fly ash (FA), ground granulated blast-furnace slag (GGBS), palm oil fuel ash (POFA), volcanic ash, and red gypsum, have emerged as promising alternative materials for soil stabilization [6]–[8]. Compared with OPC, geopolymers offer several advantages, including reduced permeability [9], high early-age strength, rapid hardening [10], [11], fire resistance [12], self-regulating moisture behavior, and strong resistance to chemical and acid attacks [13], [14]. Moreover, geopolymerization can reduce CO_2 emissions associated with binder production by approximately 60–80%, making geopolymers one of the most promising sustainable binder alternatives currently available [15].

Recent studies have confirmed that geopolymers can significantly improve the engineering behavior of clay soils [16]. For instance, metakaolin-based geopolymers have been reported to enhance volumetric stability, reduce shrinkage, and develop stronger and denser microstructures compared with OPC-stabilized soils. Zhang et al. [17] demonstrated that geopolymer-stabilized marine clay achieved compressive strengths two to three times higher than those of cement-stabilized soil when 3–5% metakaolin-based geopolymer was incorporated. Similarly, Ouedraogo and Al-Rkaby [18] reported compressive strength values ranging from 1 to 8 MPa for clay–sand mixtures stabilized with Class C fly ash-based geopolymers, compared with values below 0.3 MPa for untreated specimens. Their findings also indicated that increasing the sand content reduced the optimum alkaline activator-to-binder ratio from 0.8 for clay containing 5% sand to 0.6 for clay containing 10–30% sand. Advances in nanotechnology have further expanded the possibilities for enhancing geopolymer performance. Various nanomaterials, including nanosilica, nanoclay, graphene derivatives, titanium dioxide nanoparticles, nanokaolin, carbon nanotubes, and nanoaluminum, have been incorporated into geopolymer matrices to improve thermal and chemical stability, moisture resistance, and mechanical performance [19], [20]. In particular, recycled glass powder (RGP) has attracted considerable attention because of its high silica content and approximately 13% sodium oxide (Na_2O) content, which can reduce the need for highly concentrated NaOH or Na_2SiO_3 solutions in the alkaline activator [21]. Since RGP-based geopolymers can be synthesized under ambient conditions without requiring substantial thermal energy input, they offer considerable environmental and economic benefits [22].

2. Materials and Methods

The experimental program of this study was designed to evaluate the effectiveness of a geopolymer derived from Baqeran Natural Pozzolan (BNP) for clay soil stabilization under ambient curing conditions. BNP was selected based on its high SiO_2 and Al_2O_3 contents and its potential to serve as an aluminosilicate precursor. To provide a comprehensive assessment of the stabilization performance, unconfined compressive strength (UCS) testing was adopted as the primary indicator of compressive strength and load-bearing capacity, while dynamic simple shear testing was employed to determine cyclic stiffness and damping ratio under repeated loading conditions. Furthermore, scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) were used to establish correlations between mechanical improvements, gel formation, and microstructural changes. The experimental methodology comprised a series of standard soil characterization tests, mixture preparation procedures, and analytical techniques, which are described in the following sections.

3. Discussion and Results

The results of this study demonstrated that the stabilization of clay soil using Baqeran Natural Pozzolan (BNP), particularly in the presence of alkaline activators, resulted in substantial improvements in the mechanical properties and dynamic behavior of the soil. The extent of these improvements depended on the BNP content, the type of alkaline activator, and the curing period. The objectives, testing procedures, and key output parameters of the mechanical and microstructural testing program are summarized in Table 1.

Table 1. Mechanical and Microstructural Testing Program

Test Type	Purpose	Method	Key Output Parameters	Standard / Notes
UCS	Evaluate mechanical improvement due to geopolymerization or cement stabilization	UCS testing after 7, 14, and 28 days of curing	Peak compressive strength, failure mode, mean UCS value	ASTM D2166
Simple Shear	Evaluate of Dynamic Improvement Resulting from Geopolymerization Stabilization	Simple Shear testing after1day of curing	Shear Modulus (G) and Damping (D)	ASTM D6528
XRD	Identify crystalline phases and mineralogical changes	XRD scanner; 2θ range: 0–80°	Mineral phases, peak intensity changes, crystallinity	Instrument-based method
XRF	Determine oxide composition of raw materials and selected mixtures	XRF analyzer	SiO_2, Al_2O_3, Na_2O, K_2O, CaO, Fe_2O_3, LOI	Instrument-based method
SEM	Examine microstructure, pore refinement, gel formation, and particle bonding	SEM imaging	Morphology, matrix densification, gel–particle interactions	Instrument-based method

Figure 1 illustrates the variation of horizontal strain over time. A key observation is that the strain amplitude increased in a stepwise manner throughout the test. Each amplitude level lasted approximately 100 seconds, with positive and negative strain values reflecting the reversal of the horizontal deformation direction during the cyclic loading.

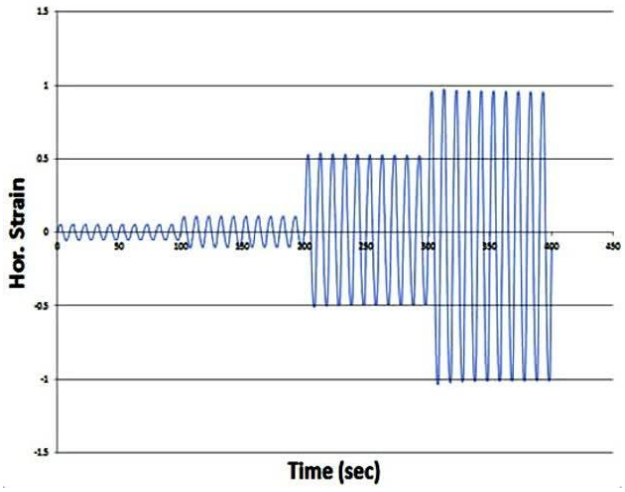

Figure 1. Variations of horizontal strain versus time.

4. Conclusion

• The results of this study demonstrated that the stabilization of clay soil using Baqeran Natural Pozzolan (BNP), particularly in the presence of alkaline activators, led to considerable improvements in the mechanical properties and dynamic behavior of the soil. The extent of these improvements depended on the additive content, the type of alkaline activator, and the curing period.

• The results of dynamic tests indicated that the addition of a geopolymer led to an increase in the shear modulus and a decrease in the damping ratio compared to the natural soil. Furthermore, an increase in the surcharge and a longer curing period were generally associated with an increase in the shear modulus. The effect of the additive percentage on these parameters was not uniform; based on the reported results, the variations observed in the specimen containing 10% additive were greater than those in the specimens containing 20% and 30% additive.

• Scanning electron microscopy (SEM) observations revealed that the soil microstructure in the activated specimens evolved from a relatively loose and porous fabric into a denser structure characterized by stronger interparticle bonding. Furthermore, energy-dispersive X-ray spectroscopy (EDX) results confirmed the presence of Si, Al, and Na in the reaction products. The mixture containing 30% BNP activated with NaOH exhibited the highest 28-day unconfined compressive strength (UCS), reaching 3,500 kPa, whereas the mixture containing 20% BNP activated with sodium silicate (Na_2SiO_3) achieved a UCS of 3,300 kPa.

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